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|  |  |  | 30.07.2025 |

**Manuscript submission**

Dear Prof. Dr. Samir Khanal,

Dear editorial board,

We are pleased to submit the manuscript “Multi-stage model predictive control of agricultural anaerobic digestion plant with uncertain substrate characterization” for consideration in Bioresource Technology.

All authors mutually agree to this submission to Bioresource Technology and declare no conflict of interest. We affirm that the manuscript contains original work of the authors. The manuscript has neither been previously submitted to Bioresource Technology nor is it currently under consideration by any other journal.

The presented investigation is assigned to the subject class “50.090 Optimization of Bioprocesses” (Bioprocesses).

Agricultural anaerobic digestion (AD) plants in Germany need to adopt more innovative strategies to remain profitable without governmental subsidies. In contrast to conventional baseload operation at steady-state conditions, promising alternatives lie in demand-oriented cogeneration, biogas upgrading, or utilization of low-cost substrates. One potential approach to achieve these alternatives is the dynamic optimization of substrate amount and composition. However, when manipulating the substrate supply, stable process conditions must be ensured at all time, particularly when using unknown substrates with uncertain feedstock characterization.

An established method for dynamic, model-based optimization is model predictive control (MPC), which has been applied to AD in the literature. However, since uncertainty of model predictions increases with the length of the prediction horizon, uncertain model parameters, such as influent concentrations, can result in instabilities in closed-loop optimization. To this end, a robust MPC framework that explicitly considers model uncertainties in the dynamic feed optimization of AD is still missing.

In the present study, we developed a multi-stage MPC framework which explicitly considers the uncertain influent concentrations of agricultural substrates, and specifically addresses the error bands of fermentable macronutrients. We applied the multi-stage MPC framework to a simplified variant of the Anaerobic Digestion Model No. 1 (ADM1), which was proposed in a previous publication in Bioresource Technology (DOI: 10.1016/j.biortech.2021.125124) and includes process inhibition of acetoclastic methanogens and the calculation of pH. The AD model was further extended by a gas storage model with explicit ordinary differential equations (ODEs).

The implementation was applied to two operational case studies, covering biogas upgrading and demand-oriented cogeneration. It can be shown that multi-stage MPC successfully tracked constant methane production setpoints; ensured safe gas storage limits; and kept process conditions stable despite uncertain substrate characterization and additional disturbances. The proposed framework thereby demonstrates the capabilities of model-based feed optimization and showcases potential avenues for more profitable operation of agricultural AD plants, especially in the light of uncertain model parameters such as influent concentrations.

Therefore, we believe that our work is well-suited for publication in Bioresource Technology.

We greatly appreciate your time and consideration.

Please do not hesitate to contact me, if you have any questions.

Sincerely,



Prof. Dr. Sören Weinrich